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WORKSHOP ON MQW MIXING AND ITS APPLICATION TO OPTOELECTRONIC DEVICES

HOTEL DE FRANCE,
ST HELIER, JERSEY

18th - 21st SEPTEMBER 1990

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ORGANISING COMMITTEE:

B L Weiss (Chairman)
University of Surrey

J M Zavada
European Office of the US Army

B J Sealy
University of Surrey

D Sadana
IBM

M Littlejohn
US Army/North Carolina State University

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GENERAL INFORMATION

The meeting will be held in The Regency Room. The refreshments will be in The Minstrel Bar and the workshop office will be in Board Room 1 and will be manned during the following hours each day by Mrs Karen Arthur

08.30 - 09.30
13.30 - 14.30
17.00 - 17.30

If you need to be contacted the following may be of use

Telephone. Jersey (0534) 38990 ext 831
FAX: Jersey (0534) 30874
Telex: 4192308

Quoting Workshop on MQW Mixing

For those departing on Friday, two rooms will be available to store luggage and freshen up in as people must check-out by 10.00am.

The hotel accept Access, Visa, American Express and Diners Club credit cards

PROGRAMME

TUESDAY 18th SEPTEMBER

18.00	Registration in the Arcade Area
19.00 - 20.30	Welcome Reception in the Imperial Lounge
20.30	Dinner in Restaurant

WEDNESDAY 19th SEPTEMBER

09.00 - 09.15	"Introduction" B L Weiss and J M Zavada

Mixing Processes and Characterisation

Chairman: B J Sealy

09.15 - 09.50	"GaInAs(P)-InP MQW Mixing by Zn Diffusion, Ge and S Implantation for Optoelectronic Applications" F H Julien*, E V K Rao+, M Razeghi& and L Goldstein$ * Institut d'Electronique Fondamentale, Universite Paris-XI, France + Centre National d'Etudes des Telecommunications, Bagneux, France & Thomson-CSF, Orsay, France $ Laboratoire de Marcoussis CR-CGE, Marcoussis, France
09.50 - 10.25	"Atomistic Mechanisms of Dopant Induced MQW Mixing" U Gosele, S Yu and T Y Tan Department of Mechanical Engineering and Materials Science, School of Engineering, Duke University, USA
10.25 - 10.40	REFRESHMENTS
10.40 - 11.15	"Enhanced/Suppressed Interdiffusion of Lattice Matched and Pseudomorphic III-V Heterostructures by Controlling Ga Vacancies" R M Kolbas, Y L Hwang, K Y Hsieh, T Zhang and U K Mishra North Carolina State University, USA
11.15 - 11.50	"Quantum Well Shape Modification Using Vacancy Generation and Rapid Thermal Annealing" E S Koteles, B Elman, P Melman, J Y Chi and C A Armiento GTE Laboratories Inc, Waltham, MA, USA
11.50 - 12.25	"Cation Diffusion in InP/$In_{0.53}Ga_{0.47}As$ Superlattices: Strain Build-Up and Relaxation" D M Hwang, S A Schwarz and R Bhat Bellcore, Red Bank, New Jersey, USA
12.25 - 14.00	LUNCH IN RESTAURANT

Mixing Process and Characterisation Contd

Chairman: D Sadana

14.00 - 14.35	"Advanced Materials Characterisation of Electronic Device Structures" R T Lareau US Army LABCOM, SLCET-EJ, Fort Monmouth, New Jersey, USA
14.35 - 15.10	"Raman Microprobe Study of Strain in GaAlAs Structures" H E Jackson Department of Physics, University of Cincinnati, USA
15.10 - 15.30	REFRESHMENTS
15.30 - 16 05	"Impurity Induced Compositional Disordering of InGaAs-InAlAs Multiquantum Well Structures Grown by Molecular Beam Epitaxy" E V K Rao, P Ossart, Y Gao, M Quillec, H Thibierge, P Krauz and P Blanconnier Centre National d'Etudes des Télécommunications, Laboratoire de Bagneux, Bagneux, France
16.05 - 16 40	"Zinc Diffusion in GaAs and Zinc Induced Disordering of GaAs/AlGaAs Multiquantum Wells: A Multitechnique Study" D Araujo*, J D Ganiere*, L Pavesi*, N H Ky*, P A Buffat+, G Burri& and F K Reinhart* * Institut de Micro et Optoelectronique, Ecole Polytechnique Federal de Lausanne, Lausanne, Switzerland + Institute of Electronic Microscopy, Swiss Federal Institute of Technology, Lausanne, Switzerland & Institute for Experimental Physics, University of Lausanne, Switzerland
16 40 - 17.15	"Order-Disorder Ternary Alloys by Atomic Layer Epitaxy" N A El Masry* and S M Bedair+ * Department of Materials Science and Engineering, North Carolina State University, USA + Department of Electrical and Computer Engineering, North Carolina State University, USA
19.00 - 21.30	DINNER IN RESTAURANT

THURSDAY 20th SEPTEMBER

Device Applications of MQW Mixing

Chairman: M J Littlejohn

08.50 - 09.25	"Disordering of Superlattices for Laser Applications" R G Wilson Hughes Research Laboratories, Malibu, CA, USA
09.25 - 10.00	"Band Structure Dependence of Optoelectronic Devices from High Pressure Measurements" A R Adams University of Surrey, Guildford, UK
10.00 - 10.35	"Effect of Strain in Multiquantum Well Lasers" R A Logan, T Tanbun-Ek, S N G Chu and H Temkin AT&T Bell Laboratories, Murray Hill, USA
10.35 - 10 50	REFRESHMENTS
10 50 - 11.25	"Multiquantum Well Mixing and Index Guided Quantum Well Heterostructure Lasers by MeV Ion Implantation" R P Bryan, J J Coleman, R S Averback, J L Klatt, L M Miller and T M Cockerill University of Illinois at Urbana-Champaign, USA
11.25 - 12 00	"Lasers and Waveguides with Short Period (GaAs)(AlAs) Superlattices" P Blood*, E D Fletcher+, C T Foxon+ and D E Lacklison+ * University of Wales College at Cardiff, Cardiff, UK + Philips Research Laboratories, Redhill, UK
12.00 - 12 35	"Non-Destructive Characterisation of AlAs/GaAs Superlattices by Optical Reflection" G K Hubler*, C N Waddell*, E P Donovan* and J M Zavada+ * Naval Research Laboratory, Washington DC, USA + Army Research Office, London, UK
12 35 - 14.00	LUNCH IN RESTAURANT

Device Applications of MQW Mixing Contd

Chairman: J M Zavada

14.00 - 14.35	"Disordered Delineated Waveguides in GaAlAs/GaAs and GaInAs/InP MQW Structures" B L Weiss*, A C Wismayer*, N J Whitehead*, I V Bradley*, J Roberts+ and P A Claxton+ * University of Surrey, Guildford, UK + University of Sheffield, Sheffield, UK
14.35 - 15.10	"Applications of Impurity Induced Disordering to Low-Loss Optical Waveguides and Waveguide Devices" J H Marsh, S I Hansen, A C Bryce and R M De La Rue University of Glasgow, Scotland, UK
15.10 - 15.30	REFRESHMENTS
15.30 - 16.05	"Intermixing of MQWs for All Optical Integrated Circuits" P Li Kam Wa CREOL/UCF, Orlando, Florida, USA
16.05 - 16.40	"Post Growth Tailoring of the Optical Properties of GaAs-AlGaAs Quantum Well Structures" M Ghisoni*, A Rivers*, G Parry* and J Roberts+ * University College London, UK + University of Sheffield, Sheffield, UK
20.00 for 20.30	RECEPTION AND WORKSHOP DINNER IN THE IMPERIAL LOUNGE Speaker: B J Sealy

FRIDAY 21st SEPTEMBER

Mixing and Device Applications of Strained Layer Structures

Chairman: B L Weiss

09.00 - 09 35	"Partial Intermixing of Strained InGaAs/GaAs Quantum Wells" P Melman, E S Koteles, B Elman and C A Armiento GTE Laboratories Inc, Waltham, MA, USA
09.35 - 10 10	"Thermal Interdiffusion in InGaAs/GaAs and GaAsSb/GaAs Strained Quantum Wells as a Function of Doping Density" W P Gillin*, K P Homewood*, B J Sealy*, L K Howard* and R Pritchard+ * University of Surrey, Guildford, UK + UMIST, Manchester, UK
10.10 - 10.30	REFRESHMENTS
10.30 - 11 05	"Annealing of Strained Layer InGaAs-GaAs Multiquantum Well PIN Diodes" I Harrison*, H P Ho*, A Khouni*, J P R David+, P A Claxton+ and R Grey+ * University of Nottingham, Nottingham, UK + University of Sheffield, Sheffield, UK
11 05 - 11 40	"Issues in the Realisation of Strained-Layer, Quantum-Well, Optoelectronic Elements" D R Myers Sandia National Laboratories, Albuquerque, New Mexico, USA
11.40 - 12 00	"Future Trends" J Walling and M Littlejohn
12.00 - 12 10	Closing Address
12.10	LUNCH IN RESTAURANT

LIST OF ATTENDEES

Professor A R Adams
Professor S M Bedair
Professor P Blood
Professor J J Coleman
Professor N A El Masry
Mr M Ghisoni
Dr U Gosele
Dr I Harrison
Dr G K Hubler
Dr Dah-Min Hwang
Professor H E Jackson
Professor F H Julien
Professor R Kolbas
Dr E Koteles
Dr R Lareau
Dr P Li Kam Wa
Professor M Littlejohn
Dr R A Logan
Dr J Marsh
Dr P Melman
Dr D Myers
Professor G Parry
Dr L Pavesi
Dr E V K Rao
Dr D Sadana
Professor B J Sealy
Mr C Seltzer
Dr J Walling
Dr B L Weiss
Professor M G F Wilson
Dr R G Wilson
Dr J M Zavada

ABSTRACTS

WORKSHOP ON MULTIQUANTUM WELL MIXING AND ITS APPLICATION TO OPTOELECTRONIC DEVICES
JERSEY CHANNEL ISLANDS
18th 21st SEPTEMBER 1990

GaInAs(P)-InP MQW MIXING BY Zn DIFFUSION, Ge AND S IMPLANTATION FOR OPTOELECTRONIC APPLICATIONS

F H Julien[*], E V K Rao[·], M Razeghi[@] and L Goldstein[$]

[*] Institut d'Electronique Fondamentale, URA CNRS 22, Bat 220, Université Paris-XI, 91405 Orsay, France

[·] Centre National d'Etudes des Télécommunications, Laboratoire de Bagneux, 196 avenue Henri Ravera, 92220 Bagneux, France

[@] Thomson-CSF, Laboratoire Central de Recherches, 91410 Orsay, France

[$] Laboratoire de Marcoussis CR-CGE, Route de Nozay, 91460 Marcoussis, France

There is a growing interest in impurity induced layer disordering for the technologically important InGaAs(P)/InP system. More complicated than the AlGaAs/GaAs ternary system which only concerns interdiffusion of column III atoms, interdiffusion in this quaternary system can occur equally for both column III (Ga,In) and column V (P,As) atoms, which may or may not result in a strain-free alloy lattice-matched to InP, a major concern for device applications. Moreover, due to the poor thermal stability of this quaternary compound compared to the AlGaAs/GaAs system, thermal intermixing effects cannot be ruled out. Results are presented concerning this effect. We show that moderate-temperature Zn diffusion leads to column III disordering only. On the other hand, Ge and S implantation of InGaAs/InP quantum wells results in both column III and column V interdiffusion approximating lattice-matched conditions.

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ATOMISTIC MECHANISMS OF DOPANT INDUCED MQW MIXING

U Gosele, S Yu and T Y Tan

School of Engineering, Duke University, Durham, NC 27706, USA

Dopant-induced mixing of multiquantum well (MQW) structures is due to an increase of the concentration of point defects responsible for the diffusion of atoms involved. In the case of GaAs-based MQW structures such as GaAs/$Al_xGa_{1-x}As$ superlattices the diffusion of Ga and Al atoms is mainly carried by triply negatively charged gallium vacancies in n-doped and intrinsic material and by positively charged gallium interstitials in p-doped material. Doping can influence the appropriate charged point defect concentration by two effects:

- Change in the equilibrium concentration of charged point defects due to the change in the Fermi-level.

- Generation of non-equilibrium point defects due to the diffusion process of the dopant.

For n-type dopants such as silicon in GaAs the Fermi-level effects appears to be dominant, whereas for p-type dopants dissolved on group III lattice sites such as zinc or beryllium, a combination of both effects occurs. Both zinc and beryllium diffuse via the kick-out mechanisms in GaAs and generate a high supersaturation of gallium self-interstitials during indiffusion from an outside source thus leading to extremely high mixing rates. For grown-in Be or Zn an undersaturation of gallium self-interstitials develops and thus usually no noticeable mixing occurs. We will present computer simulation results based on the kick-out diffusion mechanisms and charged gallium self-interstitials showing the dramatic difference in point defect concentration between the cases of in and outdiffusion.

Finally, we mention that doping does not necessarily enhance the MQW mixing process but depending on the outside arsenic vapour pressure, and the diffusion mechanisms of the dopants, may also reduce this process and lead to enhanced stability of MQW structures.

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ENHANCED/SUPPRESSED INTERDIFFUSION OF LATTICE MATCHED AND PSEUDOMORPHIC III-V HETEROSTRUCTURES BY CONTROLLING Ga VACANCIES

R M Kolbas, Y L Hwang, K Y Hsieh, T Zhang and U K Mishra

North Carolina State University, Raleigh, NC 27695-7911, USA

The interdiffusion of Ga and Al (AlGaAs-GaAs) or Ga and In (InGaAs-GaAs) at a heterojunction can be significantly enhanced or suppressed by controlling the column III vacancies and interstitials. We have used various over pressure conditions and/or a buffer layer of GaAs grown at a low temperature (200°C, which is As rich) to significantly alter the interdiffusion coefficients of heterostructures in a lattice matched (AlGaAs-GaAs) and a lattice mismatched (but pseudomorphic, InGaAs-GaAs-AlGaAs) material system.

The interdiffusion coefficients and activation energies are determined by correlating the shift in the photoluminescence peaks with the calculated quantum well transition energies based on an error function composition profile. We will present data on the interdiffusion coefficients and activation energies for the AlGaAs-GaAs and InGaAs-GaAs-AlGaAs material systems under various over pressure conditions (Ga, As, no over pressure) at elevated temperatures (800 to 950°C). The dependence of the intermixing on the magnitude of the over pressure will also be presented for specific over pressure conditions. An explanation of why selective lateral patterning is much easier to achieve in certain over pressure conditions will be discussed.

Low temperature GaAs has become technologically important for electrical and optical isolation. We report on the successful growth of quantum wells on top of low temperature GaAs and the influence of this buffer layer on the intermixing of adjacent quantum wells.

Finally, data on the stability of ultrathin (monolayer thick) quantum wells indicates that monolayer thick quantum wells can survive for several hours at 900°C with only minor shifts in the photoluminescence emission energy.

This work provides insight to the physics of the stability of quantum well heterostructures, the design of strained layer lasers, lateral patterning, and the behaviour of monolayer thick quantum wells at elevated growth and processing temperatures.

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QUANTUM WELL SHAPE MODIFICATION USING VACANCY GENERATION AND RAPID THERMAL ANNEALING

E S Koteles, B Elman, P Melman, J Y Chi and C A Armiento

GTE Laboratories Inc, Waltham, MA 02254

The ability to precisely modify the optical properties of epitaxial semiconductor heterostructures in a spatially selective manner has exciting device implications. We have investigated the effects of vacancy generation (using either SiO_2 deposition or low energy ion implantation) followed by rapid thermal annealing (RTA) on quantum well (QW) optical transitions in different material systems as a means of achieving this goal.

The molecular beam epitaxy (MBE) grown samples usually consisted of several single quantum wells with different widths or a coupled pair of identical QWs (CDQW) located about 1 μm below the epitaxial surface. QWs in both the GaAs/AlGaAs and strained InGaAs/GaAs material systems were studied. Vacancies were generated near the surface by depositing SiO_2 films (which absorb gallium atoms during annealing producing gallium vacancies) or by ion beam damage. The latter was accomplished using ^{75}As ions with energies low enough (~35 keV) that the disordered surface regions (only several hundred Angstroms deep) were well separated spatially from the QWs. Half of each sample was masked to serve as a monitor of the effects of annealing alone on QWs. RTA was performed at 750 to 850°C for fifteen seconds for the InGaAs/GaAs QWs and up to 1000°C in the GaAs/AlGaAs system. Low temperature photoluminescence (PL) and PL excitation (PLE) spectroscopies were used to monitor exciton energies before and after processing.

After RTA, exciton energies of single QWs in both material systems shifted significantly to higher values only in regions containing surface vacancies. The magnitudes of the shifts were dependent on the widths of the QWs, annealing temperatures, and vacancy concentrations, as determined by SiO_2 thicknesses or implantation fluences. They were interpreted as resulting from the modification of the shapes of the as-grown QWs from square (abrupt interfaces) to rounded (gradual interfaces) due to enhanced diffusion of barrier and well atoms in irradiated area as a consequence of the diffusion of vacancies generated near the surface. Spatially resolved PL spectroscopy verified that the lateral diffusion of surface vacancies was less than that of the experimental resolution (ie of the order of 5 μm). PLE spectroscopy of processed CDQWs (whose excitons are especially sensitive to the symmetry of the structure), indicated the presence of strong asymmetries in the annealed samples, probably due to the unidirectional nature of the vacancy diffusion process.

Quantum well shape modification is a powerful technique for implementing novel device concepts. In particular, the ion implantation technique has the potential for simultaneous patterning, interdiffusion and modification of optical and electronic properties of quantum well structures, annealing of implantation induced defects and activation of dopants when electrically active ions are used for implantation.

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CATION DIFFUSION IN InP/$In_{0.53}Ga_{0.47}As$ SUPERLATTICES: STRAIN BUILD-UP AND RELAXATION

D M Hwang, S A Schwarz and R Bhat

Bellcore, Red Bank, New Jersey 07701-7040, USA

Alternating layers of InP and $In_{0.53}Ga_{0.47}As$ can be grown as an unstrained pseudomorphic superlattice on an InP substrate. The superlattice is stable at temperatures below 700°C. However, the diffusion of cations can be enhanced by introducing p-type dopants, such as Zn, Cd, and Be, and annealing at temperatures of 600 to 650°C[1,2]. Secondary ion mass spectrometry (SIMS) and transmission electron microscopy (TEM) are employed here to investigate the diffusion profiles and the structure evolution in these superlattices.

We find that the initial introduction of Zn ions (using a standard Zn_3As_2 sealed ampoule diffusion) homogenises the cation distributions in the superlattice region, yielding a strained superlattice of $In_{1-x}Ga_xP/In_{1-x}Ga_xAs$ with a lattice mismatch of ~3%. As the Zn_3As_2 source diffusion proceeds, Zn ions preferentially replace the cations in the P-layers from the surface and result in a $Zn_3P_2/In_{1-x}Ga_xAs$ superlattice. For a superlattice with a P-layer/As-layer thickness ratio of 4, the lattice mismatch becomes 5%. The cations in the As-layers can eventually be replaced by Zn ions also and the end product is a Zn_3P_2/Zn_3As_2 superlattice with 2% lattice mismatch. Despite the dramatic migration of the cations, diffusion of anions was not detected and the P/As layered structure remains intact. Many microtwins along the (111) planes were observed in the strained As-layers by dark-field and high-resolution lattice imaging. This system is novel in that the strain is built-up rather than reduced after diffusion and homogenisation.

When a strained heteroepitaxial layer exceeds a critical thickness during growth, misfit dislocations are formed at the interface to relieve the strain energy. The formation of these misfit dislocations may result from the bowing of threading dislocations, the growth of dislocation half-loops from the free surface, or the expansion of micro-dislocation loops inside the material. Careful examination of the dislocation gliding mechanism indicates that, in a capped strained layer, misfit dislocations can not be formed to relieve the in-plane strain energy without increasing the strain energy along the growth direction. Instead, we find that a combination of gliding and twinning mechanisms is more likely to relieve the strain energy in a capped layer. This glide-twinning strain-relaxation mechanism explains why microtwins, and not misfit dislocations, are observed in our overstrained superlattices which were defect-free before the strain build-up by cation diffusion. Microtwins have also been observed in other capped strain layers. High resolution lattice image studies reveal that many of these microtwins have glide components in them and therefore contribute to the relief of the strain energy.

[1] S A Schwarz, P Mei, T Venkatesan, R Bhat, D M Hwang, C L Schwartz, M Koza, L Nazar and B J Skromme, Appl Phys Lett 53, 1051, (1988).

[2] D M Hwang, S A Schwarz, P Mei, R Bhat, T Venkatesan, L Nazar and C L Schwartz, Appl Phys Lett 54, 1160, (1989).

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ADVANCED MATERIALS CHARACTERISATION OF ELECTRONIC DEVICE STRUCTURES

R T Lareau

US Army LABCOM, ETDL, SLCET-EJ, Fort Monmouth,
NJ 07703-5000, USA

Recent developments in state-of-the-art materials characterisation have led to advanced capabilities which are essential to accurate qualitative and quantitative analysis of III-V device structures. Improvements in depth and lateral resolution, along with lower limits of detections (ppT), aid in providing a more detailed investigation. Electron, ion, and X-ray excitation for surface analysis provide unique characterisation techniques and are often utilised with a multi-technique approach. A review of current analytical techniques/capabilities, as well as, recent electronic materials studies will be presented.

MQW structures involving processing by ion implantation, thermal diffusion, etc, typically undergo electrical, optical (PL), and chemical characterisation. Examples of electronic device structures studied by multiple techniques, including SIMS, SAM, SEM, RBS, GDMS and TEM, will be presented to indicate the advantages of complete chemical analysis.

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RAMAN MICROPROBE STUDY OF STRAIN IN GaAlAs STRUCTURES

H E Jackson

Department of Physics, University of Cincinnati, USA

After briefly reviewing the usefulness of Raman scattering in probing the physics of semiconductor structures, we will detail the use of the Raman microprobe in understanding the role of localised strain in optical waveguide structures. A new effort in optical microscopy, photon scanning tunnelling microscopy (PSTM), will then be introduced and the first results on optical waveguides will be presented.

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IMPURITY INDUCED COMPOSITIONAL DISORDERING OF InGaAs-InAlAs MULTIQUANTUM WELL STRUCTURES GROWN BY MOLECULAR BEAM EPITAXY

E V K Rao, P Ossart, Y Gao, M Quillec, H Thibierge, P Krauz and P Blanconnier

Centre National d'Etudes des Télécommunications,
Laboratoire de Bagneux, 196 avenue Henri Ravera,
92220 Bagneux, France

Most of the published data on impurity induced disordering of InGaAs-InP multiquantum wells (MQWs) lattice matched to InP highlighted the complexity of this system (as compared to GaAs-AlGaAs). This is due basically to the requirement of simultaneous interdiffusion on both group III (Ga and In atoms) and group V (As and P atoms) sublattices and an eventual influence of the lattice mismatch on the interdiffusion coefficients. On the contrary the disordering of InGaAs-InAlAs MQWs (also lattice matched to InP) requires interdiffusion only on group III sublattice (Al, Ga and In atoms) much like in GaAs-AlGaAs. In spite of this apparent simplicity, excepting two recent reports, this system has not been investigated extensively.

Owing to the excellent quality of the presently available material and as a part of the programme aimed at developing optical devices, an investigation of interdiffusion in the InGaAs-InAlAs MQWs grown by MBE is undertaken. As is described in this communication, several crucial issues related to MQW disordering namely, thermal stability, interdiffusion enhancement by acceptor or donor dopant as well as a non-dopant impurity have been explored. The principal results of this study are as follows:

- Although these MQWs were grown at low temperatures, they exhibited remarkable thermal stability with little or no degradation for long duration furnace anneals at 750°C for one hour and short period ten second anneals up to ~850°C.

- Thermal diffusion of commonly employed acceptor impurity Zn leads to a severe enhancement of group III atom interdiffusion. The threshold concentration (atomic of carrier) for achieving complete mixing has been determined.

- Sulphur is chosen as the donor impurity because of its non-amphoteric nature and high solubility (in InP base materials). A high degree of intermixing nearing completion has been achieved for the first time by performing S implantation and subsequent annealing.

- Since devices at one stage or another require intermixed regions with some degree of electrical isolation, oxygen is chosen as the non-dopant impurity (no known shallow level as an isolated centre and besides it is often implanted in many III-V materials to realise thermally stable electrical compensation). It is demonstrated for the first time that oxygen implants followed by adequate anneals lead to a severe disordering (close to completion). Furthermore, oxygen is shown to possess a specific role, other than implant damage, to enhance interdiffusion.

All the above data will be presented and discussed with reference to mechanisms proposed already to understand the enhancement of group III atom interdiffusion in GaAs-AlGaAs system.

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ZINC DIFFUSION IN GaAs AND ZINC INDUCED DISORDERING OF GaAs/AlGaAs MULTIQUANTUM WELLS: A MULTITECHNIQUE STUDY

D Araujo[*], J D Ganiére[*], L Pavesi[*], N H Ky[*], P A Buffat[+], G Burri[§] and F K Reinhart[*]

[*] Institute for Micro and Optoelectronics, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland

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[§] Institute for Experimental Physics, University of Lausanne, CH-1015 Lausanne, Switzerland

Zinc diffusion on Si-doped GaAs ($n \simeq 10^{18}$ cm^{-3}) samples were carried out in a sealed evacuated quartz tube with $ZnAs_2$ source. Different diffusion temperatures (from 575°C to 700°C) have been used to study the mechanism of the diffusion. We have characterised the diffused samples by secondary ion mass spectrometry (SIMS) and by scanning electron microscopy (SEM) using different imaging modes such as secondaries (SE), cathodoluminescence (CL) and electron beam induced current (EBIC). The Zn diffusion depths measured by SIMS, fits well with the p-n junction positions given by SE and EBIC. The temperature dependence of the diffusion coefficients results in an activation energy for the Zn diffusion of 2.19 eV. The non-exponential decay of the low temperature EBIC signal observed on the p-side of the p-n junction could be related with the zinc impurity concentration gradient measured by SIMS. Room and liquid nitrogen temperature photoluminescence (PL) measurements on the diffused samples show that gallium vacancies play an important role on the mechanism of the Zn diffusion. In particular, a luminescence band associated with a Ga vacancy-donor complex have been detected in the as-grown samples. After Zn diffusion, this band disappears supporting the Longini model of Zn diffusion into GaAs.

We have studied the impurity induced disordering (IID) of MQW by transmission electron microscopy on a wedge shaped specimen (WTEM) to obtain local information on the topological disordering depth and to check the chemical homogeneities of the diffused samples. Zn diffusion was carried out on MQW structures grown by molecular beam epitaxy on [001] substrates. Using different diffusion times we studied the IID and we found a granular interdiffusion region. The origin of this granularity is not clearly understood yet, but it could indicate a clustering effect. An enrichment of Al at the surface has been observed by SIMS and confirmed by WTEM. Liquid helium PL spectra show the gradual disappearance of the MQW excitonic transitions as the number of the disordered layers increases. In particular, acceptor related transitions in the MQW have been observed for a short diffusion time. Increasing the IID, a strong MQW defect excitonic line dominated the PL spectra (possibly due to the high density of point defect produced by the Zn diffusion). When all the MQW are destroyed the PL spectra shows the band to band recombinations in the IID produced alloy and a strong reduction of the PL integrated emission.

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ORDER-DISORDER TERNARY ALLOYS BY ATOMIC LAYER EPITAXY

N A El Masry* and S M Bedair+

* Department of Materials Science and Engineering,
North Carolina State University, Raleigh, NC 27695, USA

+ Department of Electrical and Computer Engineering,
North Carolina State University, Raleigh, NC 27695, USA

$Ga_{0.5}In_{05}P$ ternary alloy, lattice matched to GaAs substrate was grown by Atomic Layer Epitaxy. The growth was proceeded by the deposition of monolayers of In-P-Ga-P in a self-regulated fashion. The ternary alloy was found to have different crystal and bandgap structures, depending on the growth conditions used. Film deposited on (100) oriented GaAs substrates were found to have a random (disordered) structure with Eg ≈ 1.9 eV. However, the same ternary alloy deposited on a misoriented substrate showed a high degree of ordering with Eg ≈ 1.76 eV. The ordered structure is in the form of highly strained monolayer superlattices (InP-GaP) oriented along the (111) direction. The ordered structure is of the CuPt type. The order-disordered transition can also be achieved by Se doping in the range to $10^{18}/cm^3$.

We will report on the atomic layer epitaxy growth conditions for both ordered and disordered GaInP films. The structural and optical properties of these films will be presented. We will also discuss several possible device structures based on this ternary alloy with the same chemical composition but with different bandgap.

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DISORDERING OF SUPERLATTICES FOR LASER APPLICATIONS

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Implantation of non-dopant ions into heated III-V superlattices is being investigated as a technique to intermix quantum-well and barrier materials. Intermixing by implantation of non-dopant ions is of interest for optoelectronics devices because of the potential reduction of free-carrier absorption loss in the intermixed regions. We have implanted Ne ions into GaAs/AlGaAs MQW and SQW samples at 500°C. Intermixing of Ga and Al atoms of the MQW material is characterised using SIMS to depths that exceed 0.5 µm. The intermixing is also characterised by examining the shift in energy of low temperature photoluminescence from SQW layers located at various depths beneath the sample surface. Stripe patterns were formed in some samples and the lateral distribution of the intermixing and the material damage are examined using SEM techniques.

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BAND STRUCTURE DEPENDENCE OF OPTOELECTRONIC DEVICES FROM HIGH PRESSURE MEASUREMENTS

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When hydrostatic pressure is applied to III-V semiconductors the Γ minimum moves up swiftly with respect to the top of the valence band (~10 meV/kbar), the L minima move up at about 5 meV/kbar while the X minima move down at about 1.5 meV/kbar. These movements approximately mirror the effects of mixing on the band structure and high pressure measurements can be useful in determining whether a particular phenomenon will or will not be sensitive to interatomic mixing.

The results of hydrostatic pressure measurements on both long wavelength (1.5 μm) and short wavelength (0.8 μm) quantum well lasers will be presented. These low field devices are shown to be extremely sensitive in their separate ways to the exact details of the band structure in the well or in the barrier regions.

By contrast, high field effects such as impact ionisation and hot carrier injection generate carriers in high energy regions of the band structure which depend less sensitively on the effects of pressure and mixing. We have demonstrated this experimentally via high pressure measurements of avalanche breakdown. The results for a variety of materials will be compared and contrasted. We have also shown theoretically using a Monte Carlo simulation that no enhancement of the election ionisation rate will be obtained from GaAs/AlGaAs MQW devices due to hot electron injection from the wide gap barriers as has been proposed, since the average electron energy is almost independent of the Γ minimum.

In conclusion, high pressure experiments can be useful in identifying the key features of the band structure which must be considered when engineering a device using mixing techniques.

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EFFECT OF STRAIN IN MULTIQUANTUM WELL LASERS

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A survey of graded index separate confinement multiquantum well distributed feedback (GRIN-SCH-MQW-DFB) lasers compares the effects of strain in the quantum well upon threshold, output power and linewidth. Lasers with either compressive or tensile strained quantum wells and a long cavity show lower threshold current (10 to 20 mA) and higher output power, respectively, than is observed with unstrained quantum wells. In non-DFB lasers, the strain induced by varying the In concentration in the QW from x = .48 to x = .62 results in the lasing wavelength shift from 1.45 to 1.62 μm. At the wavelength of 1.48 where Er doped fibre amplification is achieved, a laser output of 206 mW has been obtained. In lasers with DFB, an optical output exceeding 100 mW has been achieved. While these high output powers have been obtained, the reduced cavity loss introduced by strain has also permitted formation of QW lasers with sub mA threshold currents. Recent studies of the thermal stability of the quantum well structures, as a function of strain, will be described.

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MULTIQUANTUM WELL MIXING AND INDEX GUIDED QUANTUM WELL HETEROSTRUCTURE LASERS BY MeV ION IMPLANTATION

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Impurity induced compositional disordering of III-V compound semiconductor epitaxial structures has potential for the microfabrication of unique optical and electronic devices. Compositional disordering of thin layer AlAs-GaAs superlattices (SLs) has most commonly been induced with the electrically active impurities Zn and Si which are introduced into the crystal by either diffusion or ion implantation. For many applications, however, the incorporation of electrically active impurities may be undesirable and recent reports indicate that compositional disordering can be induced through implantation of the lattice constituents Ga, Al, and As, or other electrically inactive impurities, such as Kr, B, and F. In this work, we describe the results of our study of MeV implantation of oxygen and krypton into AlAs-GaAs superlattices and the fabrication of index guided quantum well heterostructure lasers by MeV oxygen ion implantation.

Important considerations for ion beam mixing are the damage the irradiation introduces into the sample, the ability to anneal such damage, and the efficiency with which the superlattice can be disordered. An important parameter for all three of these concerns is the sample temperature during the mixing irradiation. MeV implantation of oxygen into AlAs-GaAs superlattices is shown to result in induced compositional disordering and the formation of a semi-insulating layer at a depth of ~1.25 µm. The degree of induced disorder was examined for several different doses and implant temperatures. The compositional structure of the superlattice was studied by secondary ion mass spectroscopy (SIMS) for the as-grown, implanted, and annealed cases. Depth profiles indicate no detectable compositional disordering for doses below 10^{17} cm^{-2} and partial disordering prior to annealing for a dose of 10^{17} cm^{-2}. Following annealing samples implanted at room temperature exhibit enhanced disordering resulting in complete intermixing of adjacent layers over a range of ~3500 Å. In contrast, annealing of samples implanted at 250°C produces no further disordering. Electrical measurements indicate the formation of both a thermally stable semi-insulating layer and a compositionally disordered region formed in an AlAs-GaAs superlattice by high energy oxygen ion implantation and annealing.

The influence of the specimen temperature during MeV Kr irradiation on the extent of compositional disordering in GaAs-AlAs superlattices has been determined. We show the unexpected result that the mixing efficiency decreases with increasing substrate temperature between room temperature and 523 K, the highest temperature employed in this work. The implication of this observation is the existence of a miscibility gap in the coherent phase diagram of the GaAs-AlAs superlattice system (wavelength ~400 Å) with a critical temperature greater than 523 K.

In recent years, considerable interest has been shown in impurity induced compositional disordering of III-V compound semiconductor devices especially in efforts directed towards fabricating index-guided buried heterostructure (BH) lasers. We describe here the fabrication of BH graded barrier quantum well (GBQW) lasers by MeV oxygen ion implantation in which we utilise the compositionally disordering and semi-insulating characteristics of oxygen implanted AlGaAs layers. We observe that low

dose implants (10^{14} cm^{-2} to 10^{16} cm^{-2}) are sufficient to eliminate leakage current in laser devices by the formation of a semi-insulating region but insufficient to induce compositional disordering, thus resulting in gain-guided laser operation. High dose implants (10^{17} cm^{-2}) are able to induce compositional disordering and hence index-guided laser operation but, as a consequence of the lateral distribution of oxygen under the implantation mask, also partially compensate the stripe region thereby greatly increasing the threshold current for narrow stripe widths (<5 μm).

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LASERS AND WAVEGUIDES WITH SHORT PERIOD (GaAs)(AlAs) SUPERLATTICES

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Short period superlattices of $(GaAs)_N(AlAs)_M$ with N = M have effective direct band gaps which vary with the period (N and M are the numbers of monolayers). This implies that differences in refractive index also occur, which offer the possibility of making a waveguide between a superlattice and alloy with the same average composition. The alloy can be made either by disordering the superlattice itself, or directly by epitaxial growth. In contrast to normal MQW systems, there is electronic coupling through these superlattices and they can, therefore, be used for the waveguide region of a laser. To design devices using waveguides made by disordering superlattices of this kind it is necessary to know the refractive index difference between the alloy and superlattice.

Using molecular beam epitaxy, we have grown laser structures comprising a single 58 Å GaAs quantum well within an [8 + 8] (GaAs)(AlAs) superlattice waveguide/barrier region of overall width 2500 Å; this is surrounded by outer cladding layers of $Al_{0.5}Ga_{0.5}As$ alloy. We have measured the beam divergence of this laser in a direction perpendicular to the plane of the waveguide, and from this have derived the refractive index step. This can be compared with the value estimated using refractive index data for an alloy having the same effective direct gap. We have made similar measurements on lasers having waveguides comprising an [8 + 4] superlattice, and an $Al_{.25}Ga_{.75}As$ alloy. Additional information has been obtained from direct measurement of optical transmission spectra through [8 + 8] and [4 + 4] superlattices. The direct energy gaps are in good agreement with calculation.

This work confirms the existence of refractive index steps between short-period superlattices and random alloys of the same average composition, and demonstrates their potential for the fabrication of waveguides by local disordering.

We thank M Vening, P J Hulyer and D Hilton for their help, and G Duggan for the superlattice calculations.

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NON-DESTRUCTIVE CHARACTERISATION OF AlAs/GaAs SUPERLATTICES BY OPTICAL REFLECTION

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Superlattice structures composed of alternating thin layers of III-V semiconducting compounds are being investigated for use in optical communications applications both as discrete devices and in integrated optics schemes. Device elements fabricated include distributed feedback lasers, waveguides, optical switches and light modulators. One way to define laser cavities, build diffraction gratings, or write waveguides into a superlattice structure is by ion bombardment, which <u>always increases</u> the refractive index of semiconductors. In order to make use of ion bombardment index modification, precise values of the optical constants as a function of bombardment parameters are needed. The purpose of this paper is to report the results of our optical characterisation of as-deposited superlattices. These results serve as baseline data with which to compare the results of ion bombarded samples.

Optical reflection is a useful non-destructive technique for characterising the structure of semiconductors as well as determining the refractive indices. It has been extensively used to investigate ion-implanted Si, Ge, and GaAs. Laidig et al has performed reflection measurements on similar superlattices in the region 20,000 to 33,300 cm^{-1}. This work complements the results of Laidig by extending the measurement to lower frequencies (3,000 to 20,000 cm^{-1}). Detailed analysis of reflection data was performed through the use of non-linear least squares fitting of reflection data for the refractive index parameters in a multi-layer interference calculation. Properties reported here include the thicknesses of the superlattices, the average refractive index, the thickness of a layer between the superlattice and the substrate, values of the band edge shift and changes in the absorption coefficients caused by quantum confinement of the electrons and evidence of quarter wave dielectric stack behaviour. The refractive indices of AlAs in our region of measurement is reported for the first time.

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DISORDERED DELINEATED WAVEGUIDES IN GaAlAs/GaAs AND GaInAs/InP MQW STRUCTURES

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The use of implantation for impurity induced disordering and its application to the fabrication of optical waveguides in GaAlAs/GaAs and GaInAs/InP MQW structures is discussed. The work discussed here concerns disorder delineated stripe waveguides, where the refractive index of the disordered material is less than that of the undisordered material due to the non-linear refractive index against composition characteristic for the material, and produces lateral confinement in the stripe waveguide.

Symmetrical MOVPE GaAlAs/GaAs MQW structures, with a GaAlAs layer above and below the MQW layer, were implanted with 500 keV Si^+ and annealed at a temperature of 750°C for times up to five hours to cause disordering of the MQW layer. The disordering process was studied using photoluminescence to determine the composition of the mixed material. The photoluminescence results showed a direct dependence of the extent of the mixing on the temperature and time used to anneal the samples, and in some cases the amount of Al in the mixed material exceeded its average value in the MQW layer. This was thought to be due to Al diffusing out of the GaAlAs layers surrounding the MQW layer. Stripe optical waveguides, where optical confinement is due to the disordered material having a lower refractive index than the as grown material, were fabricated by masked implantation using photoresist masks. The waveguides were found to have a relatively high loss, which is thought to be due primarily to free carrier absorption as the presence of Si has been used to produce free carriers in electronic devices. Also the variation of the ratio of deep level to band edge emission, which effectively measures the extent of the disordering, was found to correlate well with the measured waveguide loss. Subsequent experiments have used alternative impurities which do not produce free carriers.

Due to the interest in long wavelength materials, waveguides fabricated in GaInAs/InP MQW structures grown by MBE have also been studied. Here the disordering was produced by the implantation of P, which was thought to be electrically inactive. Mixing studies showed that the extent of the disordering was a function of the ion dose, annealing temperature and annealing time. Stripe waveguides formed by masked multi-energy implantation and rapid thermal annealing were found to have a low loss which was determined primarily by the ion energy and dose, thereby demonstrating that it was probably due to implantation induced damage. Clearly if this were so, optimisation of the annealing process would yield lower loss waveguides.

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APPLICATIONS OF IMPURITY INDUCED DISORDERING TO LOW-LOSS OPTICAL WAVEGUIDES AND WAVEGUIDE DEVICES

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Impurity induced disordering (IID), by producing blue shifts in the bandgap of multiple quantum well structures, is emerging as a promising technology for use in the production of low-cost OEICs fabricated with possibly only one stage of epitaxial growth. We have studied the effect of boron and fluorine as disordering species, both in GaAs/AlGaAs and more recently in GaInAs/AlGaInAs. Because B and F are not active dopants at room temperature low-loss high-resistivity waveguides can be formed.

We have examined some of the criteria that the IID process must me in specific applications including: low-loss waveguides for interconnecting components on an OEIC, non-absorbing mirrors, integrated passive waveguides for line-narrowed lasers, single frequency DBR lasers, waveguides and gratings formed through IID induced changes in the refractive index. Taking the first example, in low-loss waveguide interconnects within an OEIC two parameters are important: the absorption coefficient (α) and the material resistivity (ρ). For α, an ideal target is $\alpha < 1$ dB cm^{-1} but $\alpha < 10$ dB cm^{-1} is acceptable for many applications. Interconnecting waveguides also require a reasonably high electrical resistance in order to isolate individual components, eg for a required isolation resistance of $R \geq 100$ kΩ and waveguide dimensions of 3×1 $\mu m^2 \times 0.5$ mm long, a carrier density of $n \leq 10^{17}$ cm^{-3} is needed. Neither of these targets can be met using disordering species which are active dopants (eg Si or Zn) as impurity concentrations typically $\geq 10^{18}$ cm^{-3} are required for the IID process and, in addition, the resulting carriers lead to free-carrier absorption.

The use of boron and fluorine as disordering species has been investigated in both the GaAs/AlGaAs and GaInAs/AlGaInAs material systems. In both systems F is the more effective species and can induce complete intermixing of the wells and barriers. In the GaAs/AlGaAs system, disordering of an MQW structure containing 80 Å wells and 80 Å $Al_{0.26}Ga_{0.74}As$ barriers has been investigated: using an optimised annealing temperature of 890°C, bandgap increases of up to 90 meV have been realised. QW structures with a room temperature bandgap corresponding to 1.55 μm have been investigated in GaInAs/AlGaInAs, the Al quaternary being preferred as the barrier material over GaInAsP because only the group III lattice site needs to be intermixed. The structure investigated in this case consisted of four 100 Å GaInAs wells with 50 Å barriers of $In_{0.53}Ga_{0.27}Al_{0.20}As$. Working at an optimised annealing temperature of 650°C it was found that while B resulted in negligible bandgap changes, F was a very active disordering species producing bandgap increases >40 meV after one hour.

Optical waveguides in the GaAs/AlGaAs system have been characterised in terms of their propagation loss and refractive index. Using fluorine implanted at a concentration of $\approx 10^{18}$ cm^{-3} we have demonstrated total waveguide losses below 4.7 dB cm^{-1}, accompanied by room temperature (p-type) carrier densities in the 10^{16} cm^{-3} range. In contrast, the lowest reported absorption coefficients using Si IID are around 39 dB cm^{-1} (9 cm^{-1}), resulting either from free-carrier absorption or from band tail absorption in the case of very small induced bandgap shifts. We have also measured the refractive index changes which accompany the disordering process by using a grating coupler formed in low-index material on top of

an MQW waveguide. Substantial changes, >1%, in the refractive index were obtained at certain wavelengths in partially disordered material in the wavelength range of 820 to 910 nm. As expected, fluorine was found to produce larger index changes than boron for similar annealing conditions.

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INTERMIXING OF MQW's FOR ALL-OPTICAL INTEGRATED CIRCUITS

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All-optical switching has been demonstrated in zero-gap directional couplers fabricated in GaAs/AlGaAs single and multiple quantum well structures. The switching is a result of an intensity dependence of the refractive index of the quantum wells. This non-linear effect is negligible at small photon energies where the material is transparent. However, the non-linear refractive index is greatly enhanced near the bandgap when the absorption of photon generates carriers in the conduction and valence bands through the creation of free excitons. These free carriers in turn screen the exciton via Coulomb screening and phase space filling resulting in a change in the absorption spectrum. Another important effect arising from the creation of free carriers is the resulting Moss-Burstein shift of the absorption edge (bandgap filling). The causality between the real and imaginary component of the dielectric constant dictates a corresponding change in the refractive index which can be significant even at photon energies some 20 meV below the main excitonic resonance. The main drawback of this non-linearity is the requirement that photons have to be absorbed in order to obtain the enhanced effect. The advantage of the zero-gap directional coupler compared to the conventional twin-guide directional coupler is the significantly reduced critical coupling distance over which near complete power transfer takes place between the modes. For example all-optical switching has been observed in a 500 µm long coupler.

However, in order to monolithically integrate a few all-optical switches on chip to form a circuit we require low-loss passive optical waveguides for the interconnections. It has been found that diffusion of zinc followed by a subsequent prolonged annealing causes aluminium atoms in the AlGaAs barriers to diffuse into the GaAs quantum wells resulting in an intermixed alloyed layer. The resulting intermixed layer has a higher bandgap energy than that of the original layer and is therefore transparent over the wavelength region that the switches would operate. Since the diffusion and annealing processes are compatible with the other waveguide fabrication stages, on-chip integration should be possible.

At the meeting, results of the switching characteristics of both single and multiple quantum well zero-gap directional couplers using CW and mode-locked picosecond lasers will be presented and the initial results of diffusion induced intermixing of quantum wells will be presented together with a projection on the integration of passive waveguide with switches will be discussed.

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POST GROWTH TAILORING OF THE OPTICAL PROPERTIES OF GaAs-AlGaAs QUANTUM WELL STRUCTURES

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In recent years the carrier confinement provided by the two dimensional nature of GaAs/AlGaAs quantum well structures, and the resulting clear room temperature exciton features, has led to their exploitation in a wide variety of novel optoelectronic devices, in both normal incidence and waveguide configurations[1,2]. These devices have made use of both the associated optical non-linearity, and of the electric field dependence of the optical spectra, known as the quantum confined Stark effect (QCSE). The ability to integrate active and passive devices as well as many discrete devices is an area of intense research activity.

In this talk we will discuss the post-growth bandgap engineering of both single and multiple quantum well material and its applications to optoelectronic integration. The method used is not the more common impurity induced disordering, but impurity free vacancy diffusion (IFVD)[3]. Here a controlled blue shift of the bandedge is achieved via the deposition of a SiO_x encapsulant followed by rapid thermal annealing[4]. The blue shifted samples retain clearly resolved room temperature excitonic features, and of particular importance for device applications also preserve the QCSE[5].

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PARTIAL INTERMIXING OF STRAINED InGaAs/GaAs QUANTUM WELLS

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Spatially selective, precise bandgap modification of III-V semiconductor material structures is an important technique for the design and fabrication of semiconductor based optical devices. In particular, when integrating different types of devices on a single substrate, the bandgap of each device must be modified for optimum performance at a given wavelength. The use of surface vacancies and annealing to effect such bandgap shifts has been demonstrated in the GaAs/AlGaAs material system. In this paper we report the study of this technique in pseudomorphic (lattice matched but strained) InGaAs/GaAs quantum wells grown on GaAs substrates. The bandgaps associated with this system are of interest since they can be made compatible with optoelectronic telecommunication devices. However, the presence of strain adds an extra degree of complexity.

Samples were grown by molecular beam epitaxy and vacancies were generated near the top surface of the sample by shallow $^{75}As^{+}$ ion implantation through a mask. Low energy (~35 keV) ions were used so that the damage, which was confined to a narrow region near the surface, was well separated from the quantum wells under investigation. Next, rapid thermal annealing at temperatures around 850°C caused the vacancies to rapidly diffuse into the quantum well region where they enhanced the thermally driven intermixing of the constituent atoms at the heterointerfaces. This modification of the quantum well shape from square (as-grown) to rounded increases excitonic transition energies connecting ground state levels in the conduction and valence band wells as monitored by low temperature photoluminescence spectroscopy.

In the case of strained quantum wells, annealing might also modify the strain present. In fact, the temperature at which exciton energies exhibited substantial shifts is lower than that observed in the GaAs/AlGaAs system. Higher indium atom mobilities may also be important. Exciton energy shifts were studied as a function of quantum well width, anneal temperature and ion fluences. Comparisons will be made with the GaAs/AlGaAs material system.

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THERMAL INTERDIFFUSION IN InGaAs/GaAs AND GaAsSb/GaAs STRAINED QUANTUM WELLS AS A FUNCTION OF DOPING DENSITY

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The use of strained layers in devices has already received considerable interest due to the enhanced flexibility in the electronic structure that can be achieved using strain. If these materials are to be used in realistic devices it is necessary to know how the constituents will behave when subjected to typical thermal processing conditions that may be required during device fabrication for example, after ion implantation.

We have studied the thermal stability and interdiffusion of InGaAs/GaAs and GaAsSb/GaAs single quantum wells as a function of doping introduced during growth. The interdiffusion of the group III and group V sublattices were monitored using the photoluminescence from the strained quantum well. The interdiffusion constants were measured as a function of temperature and doping concentration using a Green's function model of the interfacial mixing. This provides an exact quantitative solution of the well shaped with the interdiffusion constants uniquely defined.

Using this model we have determined the Ga/In and As/Sb interdiffusion constants for anneal temperatures up to 1050°C with both Si and Be doping at levels up to 10^{18} cm^{-3}.

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ANNEALING OF STRAINED LAYER InGaAs-GaAs MULTIQUANTUM WELL PIN DIODES

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In GaAs/AlAs multiquantum well structures, the band gap can be made larger and the refractive index smaller if the Al and Ga are allowed to interdiffuse. The size of the change is related to the amount of intermixing. The greater the intermixing, the larger the band gap and smaller the refractive index. The rate at which the layers interdiffuse depends on the type of encapsulant used. With SiO_2 masks, there is a large enhancement of the interdiffusion, whilst for the same annealing conditions, the samples encapsulated with SiN_x undergo little interdiffusion. This provides a method selectively disordering a wafer. This technology will be useful in the fabrication of integrated electro-optic devices. Most of the work so far performed has been concerned with the GaAs/AlAs system. Perhaps more important are the systems which emit light with a wavelength of approximately 1.3 µm or 1.5 µm. The current work is concerned with the possibility of using this type of technology in the InGaAs/GaAs strained layer system. The first stage has been concerned with the viability of shifting the band edge with thermal annealing. In the present experiments, samples of an InGaAs/GaAs PIN diode were annealed for various times and temperatures and the shift in the exciton transition was observed by photoluminescence. In any strained system, misfit dislocations are of paramount importance. The increase in dislocation density and defect density were therefore monitored by transmission electron microscopy and deep level transient spectroscopy. The results which were obtained in the current set of experiments will be reviewed and the implications of our data on the performance of devices will be discussed.

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ISSUES IN THE REALISATION OF STRAINED-LAYER, QUANTUM-WELL, OPTOELECTRONIC ELEMENTS

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The flexibility in bandgap engineering made possible by lattice-mismatched heteroepitaxy, when augmented by ion-beam processing for localised doping, compositional intermixing, and/or electrical isolation, has produced dramatic enhancements in the performance of optoelectronic devices. This talk examines fundamental issues in the optimisation of device performance through an understanding of the effects of ion-beam processing and lattice strain. The threshold, modulation, and waveguiding aspects of ion-implanted, planar-buried heterostructure (IPBH) lasers will be used to illustrate the issues associated with strained-layer stability, strain-induced light holes, optical confinement, and improved implant predictions, to the fabrication of optoelectronic devices from strained-layer materials.

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